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Above Room Temperature Lead Salt VECSELs

M. Rahim*, A. Khiar, F. Felder, M. Fill, D. Chappuis and H. Zogg

Thin Film Physics Group, ETH Zurich, 8005 Zurich, Switzerland

Abstract

Mid-infrared vertical external cavity surface emitting lasers (VECSEL) were developed for the wavelength range 4 to 5 µm. The devices are based on lead salt materials grown by MBE on BaF_2 or Si substrate. The VECSELs are optically pumped with a 1.55 µm wavelength laser. They are operating up to above room temperature. An output power 6 mW_p was reached at a temperature of +27°C. The VECSELs are temperature tunable and lasing is observed from ~ 4.8 µm at -60°C down to ~ 4.2 µm at +40°C heat sink temperature.

*Keywords:*VECSEL; IV-VI material; PbSe laser ; lead-chalcogenides

VECSELs are devices with attractive properties. They are usually optically pumped and therefore have high power, and are power scalable. Unlike edge emitting diode lasers, they exhibit high beam quality. Many III-V based VECSELs have been realized in the near IR-region [1]. The longest wavelength reported with III-V based VECSELs is 2.8 µm [9].

Lead chalcogenides are direct narrow gap semiconductors with NaCl structure. Unlike III-V materials, lead chalcogenides have a blue shift with increasing temperature. In this work, PbTe and PbSe were used as gain medium. For PbTe, the cut-off wavelength increases from 3.9 µm at RT to 5.7 µm at 80 K, while for PbSe, it changes from 4.5 at room temperature to 6.9 at 80 K. Adding a ternary element like Eu or Sr to PbTe or PbSe shrinks the cut-off wavelength, while adding Sn leads to longer wavelength. The useful wavelengths extend from ~2.4 µm up to ~ 30 µm.
We reported before an optically pumped VECSEL emitting at wavelengths ~ 5 µm [3]. Improved results were obtained by introducing an Al heat-spreader, maximum output power increased to 260 mW_p at 100 K [4]. In addition, we realised the first VECSEL on a Si-substrate [5]. Here we report (1) the first mid-infrared VECSEL operating up to above room temperature and (2) a new type of mid-IR VECSEL grown on Si substrate.

* Corresponding author. Tel.: +41-44 633 79 32; fax: +41-44 633 18 61.
E-mail address: mrahim@phys.ethz.ch .

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1. Above room temperature VECSEL grown on BaF2 substrate

The VECSEL consists of 850 nm PbSe grown on a BaF_2 (111) substrate. The resonant cavity is formed between a 2 ½ pairs Bragg mirror on the bottom and an external top curved mirror [fig. 1]. The mirrors consist of alternating quarter wavelength thick layers of BaF_2 as low refractive index material (n = 1.46) and $Pb_{0.93}Eu_{0.07}Te$ as high refractive index material (n = 4.55 at 100 K). The large index contrast yields a high reflectivity with a few pairs only. The device is optically pumped with a 1.55 µm wavelength laser. The VECSEL beam diameter was adjusted to match the pumped area by choosing an appropriate cavity length. The VECSEL operates in the stable regime when the cavity length is slightly shorter than the radius of curvature of the spherically curved mirror (r = 25 mm) [1, 8], where the laser mode diameter is smallest. The gain medium was grown in a resonant design; the resonant design gives highest electric fields in the active layer [2].

A thick aluminum layer is added as a heat spreader with a BaF_2 intermediate layer. Note that due to the absorption of the pump power and the large difference in the photon energy between the pump laser wavelength (1.55 µm) and the VECSEL emitted wavelengths (4.3 µm), at least 66% of the power is converted to heat.

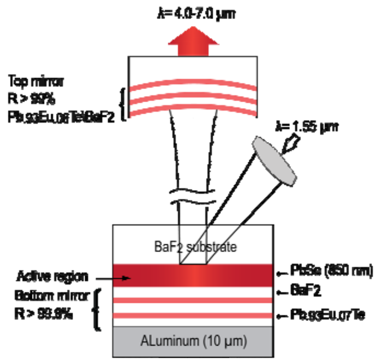

Fig. 1: Schematic cross section of a PbSe based VECSEL with resonant design [6].

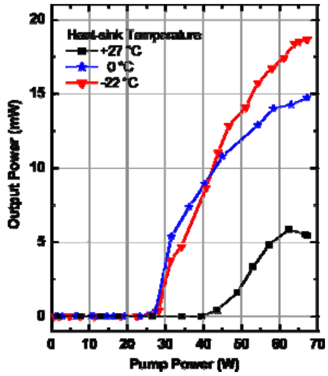

Fig. 2: Light-in / light-out characteristics at three different temperatures [6].

In Fig. 2 we present the light-in/light-out characteristic of the VECSEL in pulsed mode for 100ns pulse width and 10 kHz repetition frequency. At -22°C the threshold power was ~ 27 W and the maximum out-put power is ~ 18 mW. Even if the VECSEL design was optimize for 0°C operation temperature, where we obtained similar threshold power, at +27°C heat sink temperature the maximum output power is 6 mW_p. Lasing is observed up to +40°C heat sink temperature.

The PbSe band gap depends sensitively on temperature, while the Bragg mirror has very high reflectivity along a very large wavelength range. These properties allow the device to be tuned using the temperature. Fig. 3 shows the normalized lasing spectra for different heat sink temperature. The VECSEL has a wavelength of ~ 4.8 µm at -60°C heat sink temperature. Increasing the temperature up to +40°C allows us to tune the emission wavelength to ~ 4.2 µm. All spectra are multimode depending on the pump power. The spacing between two modes corresponds to the BaF_2 substrate optical thickness, which acts as an etalon.

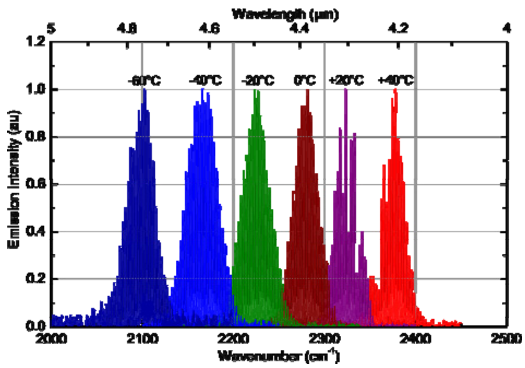

Fig. 3: Normalized lasing spectra at different heat sink temperatures [6].

2. VECSEL grown on Si substrate

Growth of epitaxial lead salts on Si substrate is possible despite large lattice constant difference with the help of thin CaF_2 buffer layer [7].
Silicon has ten times higher thermal conductivity than BaF_2. It is better suited processing. A mid-infrared VECSEL grown on Si is an attractive device.

In this part we demonstrate a mid-infrared VECSEL grown on a silicon substrate [fig.4]. Unlike the VECSEL we reported previously [5], this time the Si substrate is inside the cavity leading to better heat removal. The PbTe active medium was epitaxially grown on Si(111) with a 2 nm thick CaF_2 buffer layer. Then a 3 pair Bragg mirror with $Pb_{0.97}Sr_{0.03}Te$ as high refractive index (n = 5.8 at 100 K) and EuTe as low refractive index material (n = 2.4) was grown. Reflectance is > 99%. As before, a 1.55 µm wavelength laser is used to pump the VECSEL.

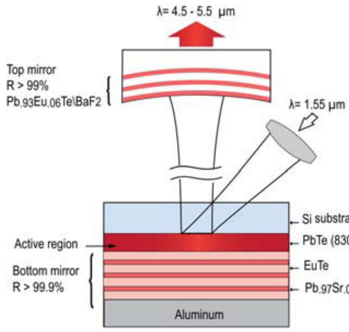

Fig. 4: Schematic cross section of a PbTe based VECSEL grown on Si substrate with resonant design.

Fig.5 (a) shows two light-in light-out characteristics at 100K temperature with 200 ns pulse width and a repetition

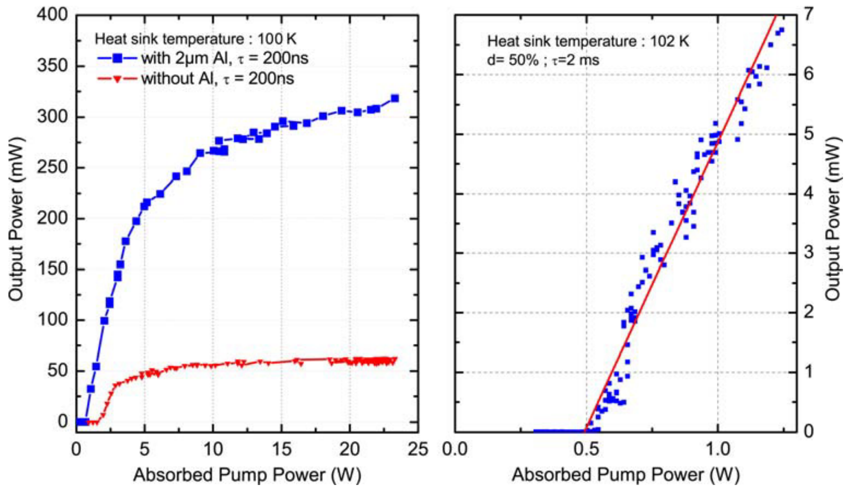

Fig. 5: Light-in / light-out characteristics at 100 K temperatures, (a) pulsed: (triangles) without Al layer and (squares) with Al layer,
(b) Continuous wave (50 % duty cycle)

frequency of 10 kHz. One is for the sample without aluminum heat spreader; it has a threshold power of ~ 2 W and 55 mW_p output power. The second is for a sample with Aluminum heat spreader separated by a quarter wavelength low refractive index intermediate layer. Here the threshold was about 200 mW_p and the maximum output power 320 mW_p.

The VECSEL grown on the Si Substrate was also operating continuous wave. For technical reasons only the light-in/light-out characteristics in quasi CW mode with 50% duty cycle (Fig.5 (b)). An output power about 7 mW was reached, and a 0.5 W threshold power was measured and a thermal rollover is observed for > 1.3 W input power.

In Fig. 6 we present the spectrum of the VECSEL output in continuous wave mode at a temperature of 100 K. The spectrum is mono-mode unlike most the pulsed excitation. The peak is centered at ~2020 cm^{-1} and has width of < 0.8 cm^{-1}.

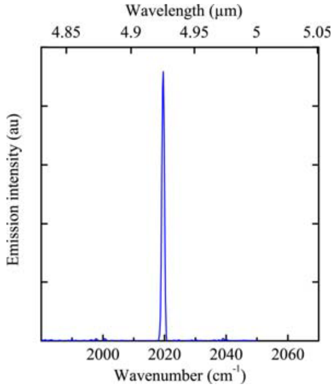

Fig. 6: Continuous wave lasing spectrum at heat sink temperature of 100 K.

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